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SHORT COMMUNICATION

Dynamic investigation of a hybrid suspension and cable-stayed bridge

P. Paultre[1,*,†], J. Proulx[1,‡] and T. Bégin[2,§]

[1] *Department of Civil Engineering, Faculty of Engineering, University of Sherbrooke, 2500 Boulevard Université, Sherbrooke, Québec, Canada J1K 2R1*
[2] *Engineering Developments, Steel-Plus Network (Canam), 11535, 1ère ave., bureau 500, St-Georges, Québec, Canada G5Y 7H5*

SUMMARY

Ambient and forced vibration tests were carried out on the Beauharnois bridge, a unique, 177-m combined suspension and cable-stayed structure near Montreal, Canada. A rehabilitation program was completed on the bridge during which the deck was completely rebuilt with an orthotropic slab on two steel trusses. The rehabilitation program also included the addition of two pairs of stay cables on both towers, creating a hybrid suspension system.

The paper presents a series of dynamic tests performed to evaluate the dynamic properties and the dynamic amplification factor (DAF) for the rehabilitated bridge. The experimental program involved the measurement of vertical, transverse, and longitudinal acceleration responses of the deck and tower under ambient and controlled traffic loads. Displacement, strain, and integrated acceleration DAFs were computed under different loading conditions. Modal properties were evaluated and used to correlate a three-dimensional finite element model for the bridge, including non-linear cable behaviour. The paper discusses the experimental setup as well as the techniques used to evaluate vibration frequencies, mode shapes, and the DAF. Correlation of numerical dynamic properties and experimental results is also presented. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: dynamic testing; modal analysis; suspension bridge; cable-stayed bridge; dynamic amplification, numerical correlation

* Correspondence to: P. Paultre, Department of Civil Engineering, Faculty of Engineering, University of Sherbrooke, 2500 Boulevard Université, Sherbrooke, Québec, Canada J1K 2RI.
† Professor.
‡ Associate Professor.
§ Director of Engineering Developments.

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1. INTRODUCTION

Most dynamic tests are carried out to evaluate dynamic properties for the calibration of finite element models [1,2] or to monitor changes in a specific bridges's dynamic behaviour. A large number of dynamic tests of short- and medium-span bridges have also been performed to determine the dynamic amplification factor (DAF) caused by traffic loads. This parameter is rarely measured for long-span cable-supported bridges. Measurement of the dynamic amplification or impact factor are needed for these types of bridges, as values found in design codes are usually limited to bridges with span lengths under 100 m. The experimental procedures used for the dynamic testing of the Beauharnois bridge under ambient and controlled traffic are presented in this paper. This bridge has the unusual feature of having a hybrid suspension and cable-stayed main structural system.

2. BEAUHARNOIS BRIDGE

The Beauharnois suspension bridge crosses the Saint Lawrence River 40 km southeast of Montreal, Canada. It has two traffic lanes, a 177-m-span and two 22.26-m-towers. This bridge was rehabilitated in 1988, which consisted of (i) a complete replacement of the roadway by an orthotropic deck supported by two transversally braced stiffening hollow-tube steel trusses; (ii) the addition of two pairs of stay cables on each tower in order to keep the existing suspension cables and increase overall bridge capacity; and (iii) the horizontal anchoring of the deck on one of the abutments to transfer longitudinal forces directly to the foundation and reduce cable loads (Figure 1(a)).

3. EXPERIMENTAL SETUP

The experimental setup is shown in Figure 1(b). Half of the symmetric deck was instrumented at each vertical hanger attachment point. Vertical, transverse, and longitudinal accelerations were obtained with eight 50-Hz force-balanced accelerometers. Three pairs of accelerometers were successively placed at each of the 14 positions on both sides of the deck. Two accelerometers remained at reference stations 1 and 2 throughout the tests, which are located half-way between the stay-cable anchor points on both sides of the deck (Figure 1(a)). Only three accelerometer configurations were necessary to cover all measurement stations on the deck. Accelerometers were also placed inside the east tower to record longitudinal and transverse motions.

In order to measure bridge vertical displacement, two linear variable differential transformers (LVDTs) were placed underneath the lower chord of the main truss at the east end of the bridge, close to accelerometer positions 29 and 30 (Figure 1(b)). Due to the heavy current of the river, LVDTs could not be placed elsewhere. However, as will be discussed below, displacements for other locations were obtained by integration of acceleration recordings.

Strain measurements were obtained on two hangers (positions S1 and S3 in (Figure 1(b)). All hangers are made of 30-mm steel cable, with the exception of hangers 12–19 (Figure 1(a)), which are made of two steel plates. Strain gauges were glued directly on hangers 16 and 19. The lower chord of the main truss was also instrumented with strain gauges at hanger 12, 19, 26 and at the location of the reference accelerometers (S2, S4, S6 and S5 in Figure 1(b)).

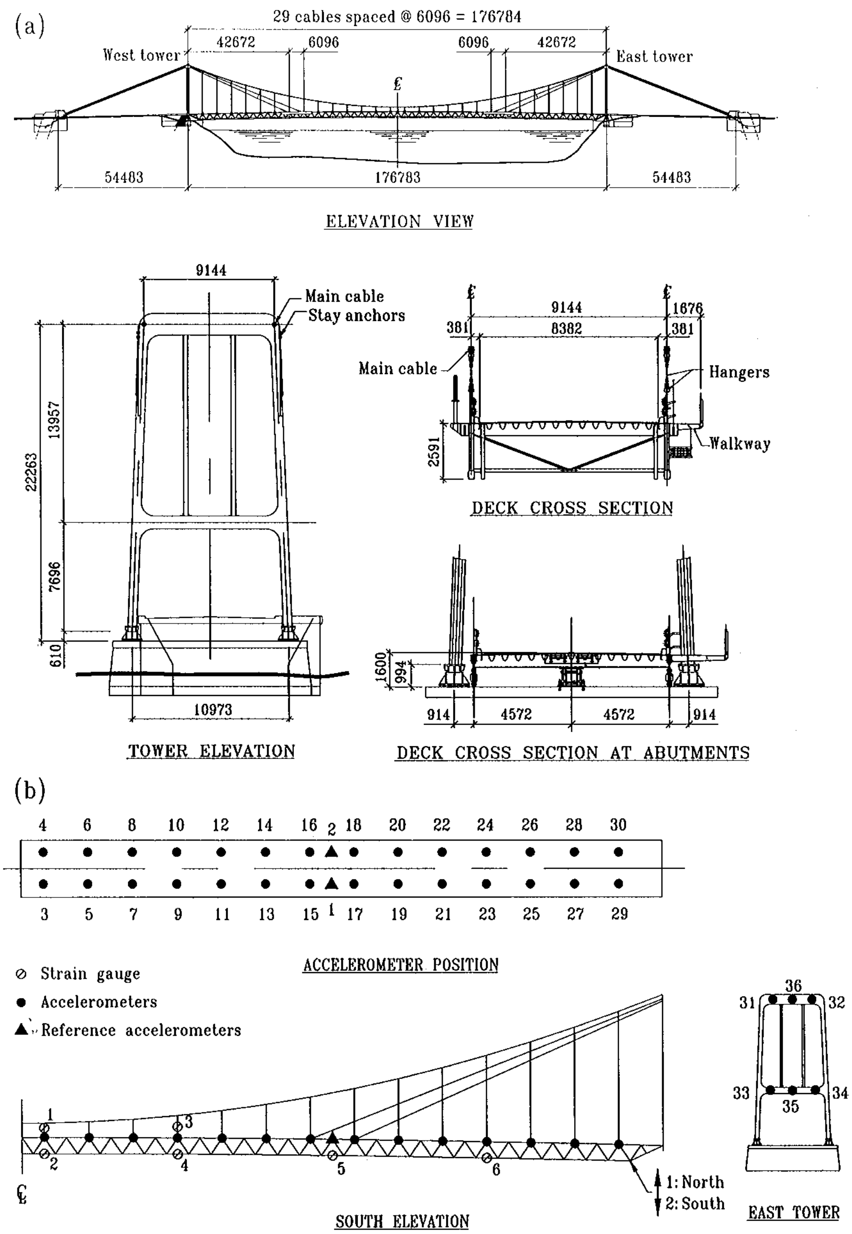

Figure 1. Beauharnois suspension bridge and instrumentation setup.

Each instrument was connected to an HP3852a data-acquisition system with track-and-hold capabilities and a 100 000-Hz aggregate sampling rate. Data was typically sampled at 100 Hz for 120 s, providing a frequency resolution of less than 0.01 Hz. Hardware filters with 20-Hz cutoff frequency were used to eliminate aliased frequencies.

4. TESTING PROCEDURE

Two different series of dynamic tests were carried out on the bridge. In the first series, acceleration data was measured under normal traffic (ambient) conditions. The second series of tests was conducted with controlled traffic to obtain the dynamic amplification factor.

The ambient vibration tests included a total of 70 recordings obtained by successively moving the accelerometers at every station on the deck and the east tower. For each position, measurements were taken in the longitudinal, transverse and vertical directions. The second series of tests was carried out with selected vehicles to evaluate the DAF. Two 280-kN, 10-wheel trucks and a 525-kN trailer were used for the tests. With traffic blocked periodically, the test vehicles completed a total of 74 runs at different speeds, positions (left, right or centre lane), and configurations (single truck, truck and trailer, two trucks in line and two trucks side by side). Average vehicle speeds, which varied from 13 to 82 km/h, were recorded with traffic counters emitting a pulse when crossed by vehicles axles (Figure 4(d)).

5. TEST RESULTS AND DYNAMIC PROPERTIES

Peak accelerations were observed on the deck in the vertical direction for both ambient and controlled traffic. A maximum acceleration of 0.20 g was obtained for two trucks driven side by side at 75 km/h. This value is twice as high as the maximum values recorded for a truck with trailer and for ambient traffic. The single truck and two trucks in line configuration produced peak accelerations of 0.19 g.

Since the input forces are not measured during the tests, the frequencies and mode shapes are evaluated by a derived modal technique. A recorded response is used as an 'input' (reference signal), while all other recordings are considered responses to this input. Cross spectra and coherence functions are evaluated and averaged for each measurement position with respect to the reference station. Resonant frequencies are obtained from peaks in the amplitude of the FFT curves for each signal, ruling out peaks with low coherence values (typically below 0.8) that are associated with local modes or bridge–vehicle interaction. Mode shapes are then determined from the peak values and corresponding phase angles [2].

Flexural and torsional modes are, respectively, separated by adding and subtracting time-domain acceleration data obtained at the same positions but on both sides of the bridge deck. This is demonstrated in Figure 2 which shows the amplitude of the FFTs obtained for a fixed position on the bridge from added and subtracted vertical acceleration responses.

6. NUMERICAL CORRELATION

A three-dimensional finite element model was developed for the bridge. The actual geometry of the stiffening girder, main suspension cables, and stays were determined by following the

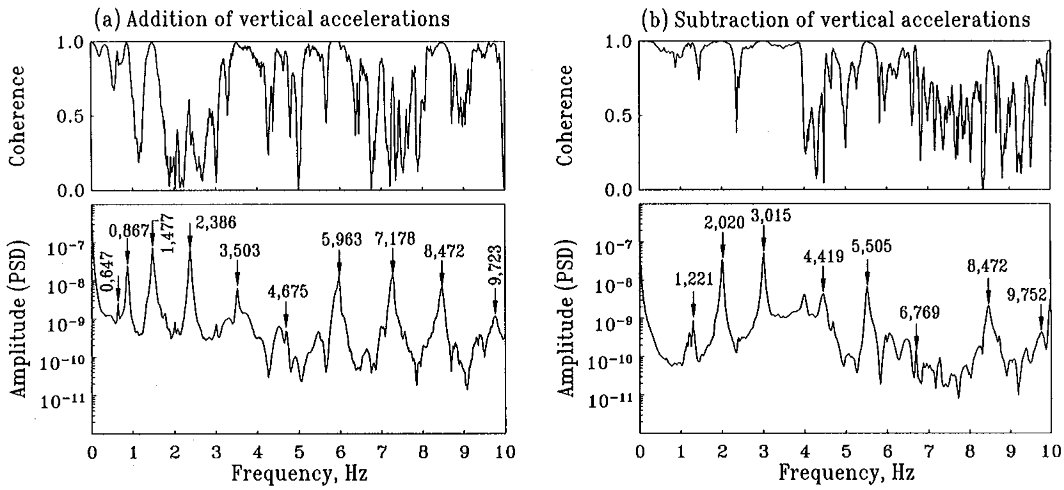

Figure 2. Frequency contents of normal traffic acceleration responses.

sequence of construction using an in-house non-linear suspension bridge analysis program. The computed geometry was then checked and adjusted with as-built geometry. Tension forces determined with the non linear program were used with the SAP90 [3] program to initialize cable forces and to determine frequencies and mode shapes for the bridge.

All cables were modelled with elements that possess axial stiffness only and whose transverse stiffness depends on cable axial tension. Single elements were used between cable connections: this does not permit the evaluation of local hangers and stay modes, which were not part of the experimental program. However, the modulus of elasticity of the stays was adjusted to account for sagging effects [4]. The stiffening girders and transverse bracing system were modelled with 3D truss elements and the towers were modeled with 3D beam elements. The orthotropic deck was modeled with plate elements having membrane and flexural stiffness. All stiffening ribs in the longitudinal direction of the steel deck were modeled with 3D beam elements.

A total of 89 modes were computed in the 0–10 Hz range. This includes 23 deck modes and 8 tower modes as well as 58 cable and local modes. Figure 3 shows the first four flexural and torsional modes identified from ambient data for the deck as well as the first two flexural and torsional modes obtained for the tower. For each mode, these shapes are compared with predicted finite element modes. The excellent agreement between measured and computed dynamic properties is confirmed by the modal assurance criterion (MAC) [5], with values ranging from 0.78 to 0.95 for the modes shown in Figure 3.

7. DYNAMIC AMPLIFICATION FACTOR

Displacement and strain values are used to obtain the DAF. In addition to the two locations where LVDTs were used, other displacement time histories were obtained by integrating

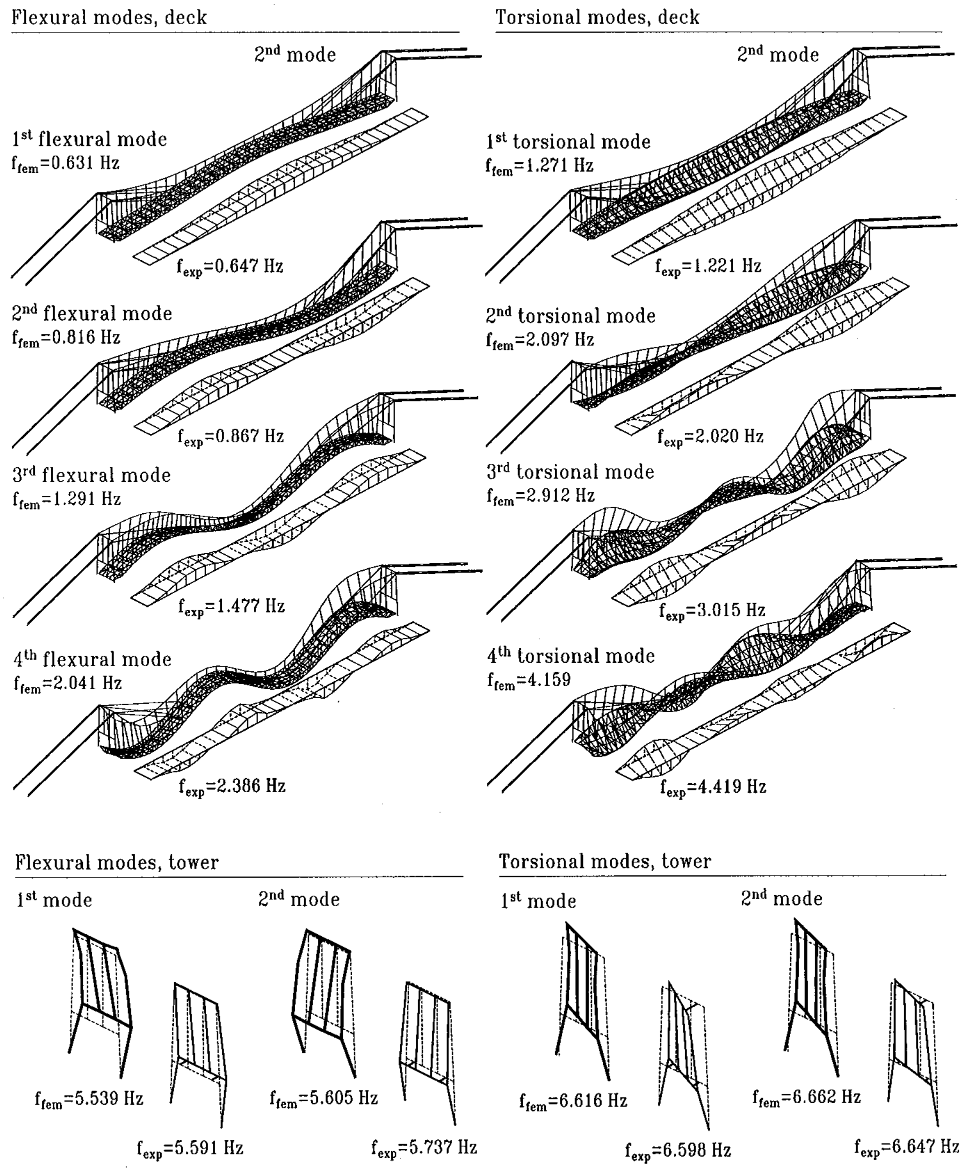

Figure 3. Computed and measured first flexural and torsional modes of the Beauharnois bridge.

acceleration recordings for each measurement station and used to compute displacement DAFs, defined as the ratio of the maximum dynamic responses to the maximum static responses. The maximum static responses were computed by applying a low-pass digital filter to remove the dynamic components from these recordings. The resulting 'static' responses, not necessarily

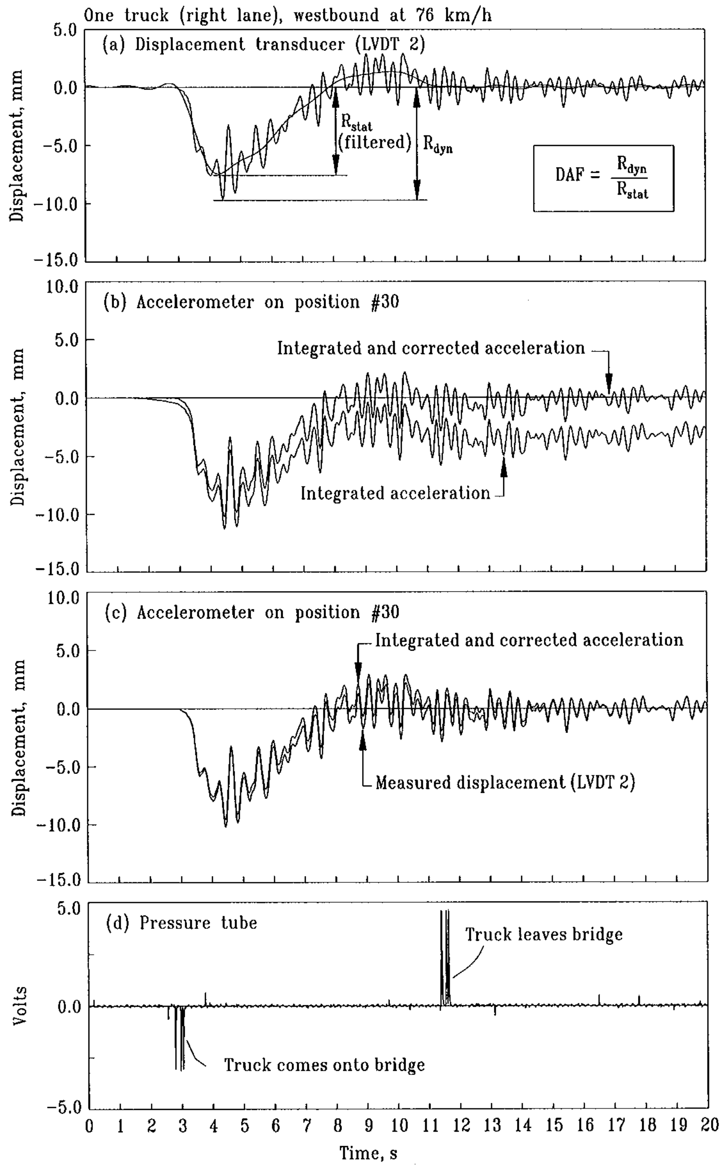

Figure 4. Determination of the dynamic amplification factor.

occurring at the same time as the maximum dynamic response, were also compared with recordings obtained during quasi-static low-speed tests (below 15 km/h). Figure 4(a) shows a recorded displacement by LVDT #2 (see Figure 1(b)). The "static" response, computed with a moving weighted-average time-domain digital-filter, is superimposed on the dynamic recording.

The maximum dynamic response and the maximum filtered static response are also indicated. Different DAF values were averaged with respect to vehicle speed, loading patterns, and position on the bridge.

In the integration process, a baseline correction is applied to the acceleration data and the remaining offsets due to the presence of very low-frequency components in the integrated displacements are eliminated by a high-pass digital filter. Figures 4(b) and 4(c) show the displacements obtained by (i) integrating the acceleration with a baseline correction and (ii) correcting the resulting displacement with a high-pass filter [2]. The integration and filtering process was calibrated with measured displacements. Figure 4(b) shows that the integration process, with appropriate corrections, results in a displacement signal that agrees with measured data. It follows that this low-cost technique can replace sophisticated but expensive optical displacement recording devices.

Table I displays average values of the DAF for strain measurements obtained on the hangers and on the deck, as well as for displacements and integrated accelerations. The minimum and maximum values correspond to the upper and lower limits of the filter parameters used to extract the static response. DAFs are higher in the case of single-truck loading. The table also shows that DAFs for strains are higher than those computed for displacements. This can be explained by the fact that the elastic force response, which is proportional to the strain response, is also proportional to the frequency squared, whereas displacements are proportional to the frequency. If higher modes are excited by bridge–vehicle interaction, larger responses can be expected for force (and strain) responses than for displacement responses.

8. CONCLUSIONS

The reliable and cost-effective procedures for dynamic testing described in this paper were applied to a rehabilitated hybrid suspension and cable-stayed bridge. Excellent agreement was observed between experimental and numerical mode shapes. An important objective of the tests was the evaluation of the dynamic amplification factor, as this is rarely measured for suspension and cable-stayed bridges. The DAF was computed for displacements, strains, and integrated acceleration responses. It was shown that the integration of acceleration data with baseline correction and

Table I. Average DAF values.

Vehicle(s)	Strains				Displacements			
	Hangers		Girders		Measured		Integrated	
	min.	max.	min.	max.	min.	max.	min.	max.
Single truck	1.28	1.29	1.19	1.20	1.10	1.11	1.06	1.07
Truck and trailer	1.12	1.13	1.08	1.09	1.03	1.04	1.01	1.02
Two trucks side by side	1.19	1.20	1.09	1.10	1.05	1.06	1.03	1.03
Two trucks in line	1.24	1.24	1.10	1.10	1.06	1.07	1.04	1.05
Average, all tests	1.20	1.21	1.12	1.12	1.07	1.07	1.03	1.04

filtering yielded reliable estimates of the displacement DAFs. Such experimental techniques are inexpensive and extremely useful for numerical model calibration.

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